Status and Perspectives of High-Power Pump Diodes for Inertial Fusion Energy Lasers

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Authors:

Constantin Häfner*, Carlo Holly, Hans-Dieter Hoffmann
Fraunhofer-Institute for Laser Technology ILT and RWTH Aachen University, Aachen, Germany
*Email: constantin.haefner@ilt.fraunhofer.de, phone: +49 241 8906 500

Lukas Gruber, Mark Crowley, Lawrence Woods, Robert Walker, Prabhu Thiagarajan
Leonardo Electronics US Inc, United States of America

Stewart McDougall, Konstantin Boucke
TRUMPF Photonics Inc, United States of America

Keeley Hurley, Guoli Lui, Juergen Jandeleit, Alex Zeitschel
Coherent, Inc, United States of America

Ralf Hülsewede
Jenoptik Diode Lab GmbH, Germany

Robert J. Deri
Lawrence Livermore National Laboratory, United States of America

Diode Pumps for Laser-Driven Inertial Fusion Energy

The record-setting Aug. 8 2021 experiment on the National Ignition Facility (NIF) yielded 1.35MJ of released energy from an imploding deuterium-tritium (DT) capsule, demonstrating a fusion gain of 0.7 and a robustly burning plasma. Although these experiments and the NIF facility are not designed to develop the physics and engineering of inertial fusion energy (IFE), the results are transformative for the risk assessment of the deuterium-tritium inertial confinement fusion (ICF) physics platform for IFE. Developing IFE based power plant remains a decadal effort and many technical challenges are ahead of us. But with this viability proof and the perspective of a carbon-free, geolocation independent power plant technology it is of utmost importance to establish a comprehensive R&D effort on all high-risk and long-term development enabling technologies. Among those needed to make IFE an attractive energy source is the development of reliable, cost-efficient high-power semiconductor lasers as economically and technically viable pumping sources for the high-energy fusion drive laser.

High-power diode lasers (HPDLs) are widely established as versatile tools for pumping of solid-state lasers and for direct materials processing. Pump applications benefit from the steadily increasing laser diode brightness over the past years. The demand for higher beam quality, efficiency and output power is achieved by continuous improvement of the emitter epitaxy and new lateral design concepts as well as improved packaging and cooling technology. Advances made in the established market in epitaxial design, manufacturing and packaging concepts benefit the development of pump sources based on single emitters (SE) and laser bars for both continuous wave (CW) and quasi continuous wave (QCW) operation. Since 2013, diode manufacturing capabilities, diode prices, and diode performance have changed dramatically. From 2013 to 2021, bar performance has increased threefold for 808 nm devices and fourfold at wavelengths above 850 nm. Due to the high Al-content for the 808 nm designs, these devices tend to be less reliable and degrade faster than the > 850 nm or even 9xx nm lasers, which utilize strained InGaAs Quantum-Wells (QW). The high-level design goals for the kW-class diode bars are increased power, efficiency, and reliability together with reduced production costs in $/W for the packaged diode pump stack. While the performance of the laser diodes has improved over the last decade, the costs are currently too high to make IFE competitive with other sources of energy. A significant reduction of cost will be needed to support the business case for IFE.

In previous designs for an IFE power plant conducted at LLNL from 2009-2013, it was found that about 60% of the cost of a laser driver is for the laser diodes, see for example LLNL's point design for a fusion power plant[Mei]. Part of the LIFE design study was the assessment for diode economies of scale in production and further technical developments, conducted in close dialog with worldwide diode manufacturers. State of the art in pulsed diode performance in 2013 was 500 W peak optical power per rod with 1.5 mm cavity length [Der13]. In this whitepaper, we provide an update on the technical progress and available diode lasers that can be used in future large-scale laser systems for IFE.

Design Parameters and Requirements

IFE drive lasers are expected to be operated at repetition rates in the range 10-Hz – 100-Hz mainly dependent on plant net electric output, architecture (fusion scheme, laser driver wavelength), fusion capsule gain and thermal to electrical conversion efficiency. Driving capsule gains of ~20…200 will require a total laser pulse energy of approximately 2 MJ to 10 MJ of UV or green light. The number of individual drive lasers to generate the total pulse energy depends on reactor chamber design and size including target stand-off, target symmetry, and economical reasons and is assumed to range from 10 kJ to 100 kJ. Laser gain media such as Nd:Glass (NIF and LIFE point design) with upper laser level lifetimes of 0.3ms require pulsed diode pumping with a minimum brightness of 15-20kW/cm^2. Assuming an optical to optical efficiency of approximately 20% for the drive lasers, 10MJ to 50MJ of laser diode energy is required, corresponding to 2 Million to 10 Million diode bars operating at today's industrial standard of 500W/bar. This is more than the current combined annual production capacity of all diode manufacturers in the world and emphasizes the need for development of higher brightness, long lifetime (MTTF) diode technology. Other laser materials (e.g. Yb:xxx, cryo Yb:xxx, Tm:xxx) with long energy storage times (1ms and beyond) may reduce the number of diodes required and shift the risk and challenges from the diode technology to other areas in the laser. Finally, laser materials with ultralong upper laser level lifetime (e.g. Tm:YLF 15ms, Tm:YAG 10ms) require either high PRF, bursts or very high fluencies to efficiently extract the stored energy – IFE architectures for this desirable laser parameter set don't exist yet though.

As a baseline for this whitepaper and for comparison to previous IFE diode technology, we consider the diode demand for an IFE laser driver to be scalable 1 kW-class bars with MTTF in the >10 Gshot range for operating wavelength 8xx nm or 9xx nm at repetition rates between 10 Hz and 100 Hz. Additional requirements are high electro-optical efficiency > 50% (~ 60%), high beam quality, and a narrow emission spectrum. We investigate pump diodes at wavelengths in the 8xx nm regime for pumping of Nd:glass, Tm:YLF, etc. and 9xx nm for Yb:YAG, Yb:CaF_2 gain media.

The reference design for the pump diode array consist of 10 mm wide bars of edge-emitting semiconductor lasers, which are vertically stacked and mounted onto a shared backplane acting as the heat-sink. In the baseline designs [Thi18] the backplane is connected to a fluid cooling system and the waste-heat is conductively transferred from the diodes to the heat-sink to keep costs and complexity low. While horizontal and vertical stacking of individual bars increases the submodules total power, the overall emitting area gets larger lowering the arrays brightness. A compromise between total power, brightness and stacking density for efficient heat removal must be made. If the modules vertical and lateral emission angles are sufficient low, there is no need for expensive external optics. The required submodules power density is in the range of 10 – 20-kW/cm². At a price target of 0.007$/W for packaged devices the pump diodes account for approximately one third of the total laser costs [Der11] for an Nd:Glass IFE driver. For a 30-year system lifetime at a repetition frequency of 15-Hz, the target lifetime is about 14 Gshots.

Today's state-of-the-art performance of kW-class laser bars

Modern bars have a format of about 10 mm x 4 mm and are manufactured using GaAs/AlGaAs/InGaAs semiconductor technology. There has been a significant increase in power output and efficiency over the last decade. However, the deployed power is enabled only with advances in reliable power. CW laser bars, for example, deployed in the Trumpf TruDisk laser product have increased from 180 W per bar in 2013 to 300 W per bar in 2021 with an increase to 350 W or even 400 W expected to be deployed over the next two years [McD20]. These improvements were made possible, among other things made possible by the continuous development and integration of Cu-based microchannel coolers.

With respect to pulsed operation, Leonardo has demonstrated output powers exceeding 500 W/bar in conductively cooled laser diode assemblies exceeding 20 kW of peak power (see Table 1 and Figure 1). These assemblies are deployed in the field and have demonstrated reliable operation within specifications for over 5 years. Leonardo leads the industry in high peak power laser diode technology and is currently deploying assemblies that incorporate laser diode bars that produce >1200 W each at efficiencies of greater than 55%. Output powers of up to 2000 W per laser diode bar have also been demonstrated [Pea15], but further improvements in diode technology and manufacturing costs are needed to make these powers industrially viable.

The main technological impetus for the performance improvements came from semiconductor-, facet-, mounting- and cooling-technologies, as well as epitaxial device design. The output power is limited by the current density in the active region, the carrier leakage [Pie15], the junction temperature, and the optical power density at the output facet, leading to catastrophic optical mirror damage (COMD). Great progress has been made in reducing absorption in the emitter facets of laser diodes and the resulting consequential damage. Long duration optical pulses and high repetition rates at average output powers exceeding 1 kW per bar require optimized epitaxial designs for high efficiency and cooling strategies to reduce device heating. The thermal limits that raise the junction temperature of laser diode emitters and limit output power result from the limited power conversion efficiency of laser diode emitters and the limited transport of waste heat generated. Higher junction temperatures lead to loss mechanisms in the active region that reduce the internal quantum efficiency of the light generation process. However, devices on active coolers and microchannel coolers are not compatible with scaling requirements for IFE laser systems due to their complexity, cost, and compactness. Conductively cooled solutions are better suited for these applications. Increasing the laser cavity length enabled higher saturation powers of low thermal resistance laser bars while maintaining efficiency. Increasing the fill factor of the laser bars led to a decrease in power density and thermal resistance while maintaining high brightness.

Table 1: Development of key parameters over the years for high peak power laser diodes deployed in the field.

Parameter	**Unit**	**HAPLS (2015)**	**Current (2021)**	**Future (2028)**
Cost	$/W	0.8	0.4	<0.1
Peak Power	kW	>20	>40	60-80
E-O Efficiency	%	60	>55	60
Repetition Rate	Hz	10-20	5-20	100
Pulse Duration	µs	300	200	300-1000
Wavelength	nm	890	8xx	8xx
Heatsink Temperature	DegC	-5 to +10	-10 to +20	35
Size	mm	11.3 x 16.9	11.3 x 16.9	Similar to current
Brightness	W/cm^2	>11	>21	30-45

Reliability requirements of the laser diode assemblies used in the IFE systems are expected to be very demanding. For bars operating at 600 W, laser diode stack lifetimes were projected to exceed 2 billion shots based on estimates from extended life test results. In addition, facet passivation technologies and epitaxial quality are advancing to support higher power bars. Manufacturing process automation is expected to be a key contributor to increases in reliability due to reductions in manual touches and improvements in process consistency.

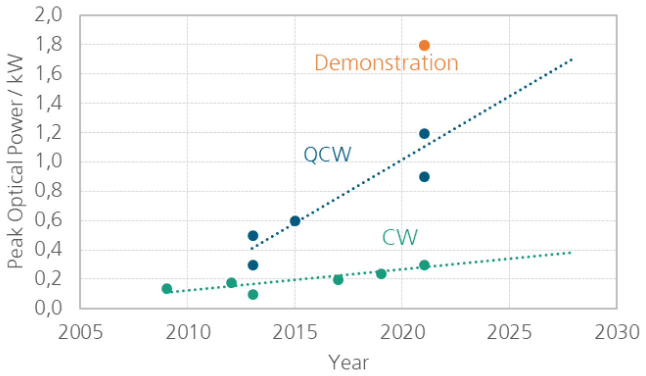

Fig. 1 Evolution of peak optical power for QCW and CW bars.

Manufacturing costs for laser diode assemblies are predominately driven by labor and overhead. Material is expected to drop by an order of magnitude to support demand needed for an IFE power plant (~500 MW). Demand for laser diodes required for an IFE power plant would increase volume by a factor of 25 over 2021 volumes resulting in a cost of ~0.02 $/W. The cost could be further reduced by considering novel designs to eliminate costly components (see Figure 2). We are optimistic that volume and target price can be met since LED production already realizes comparable demands and the high-power bar production can be transferred to existing production lines.

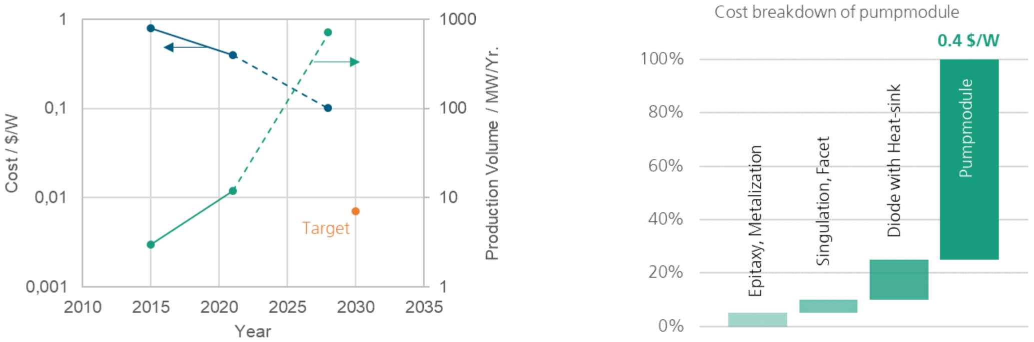

Fig. 2 Development of cost and production volume (left) and breakdown of costs for a pump module (right)

The labor component of the cost can be drastically reduced by implementing massive automation and process standardization like the silicon microelectronics industry. While this will require a large capital investment for tool acquisition, adaptation and rigorous process adjustments and improvements, it is expected to result in a reduction of the labor component cost to 0.01 $/W. Typically, III-V semiconductor substrates have a relative low wafer size of 4 inch. Processing wafers 6 inches and larger would take advantage of wafer processing automation available in the microelectronics industry. About 50% of the cost of diodes is laser bar separation and facet passivation. In addition to lowering manufacturing costs and improving yield, other technological developments to increase laser power, such as novel chip designs or thermal packaging, are improving the price per watt.

Perspective on research opportunities

In summary, it is possible to achieve high power laser diode manufacturing costs of <$0.05/W or less with the performance and reliability required for an IFE power plant in a time frame of 5-10 years. There are still technical challenges to overcome, process automation to develop, and validating volume-related economies of scale. The key component that has enabled power scaling since 2013 is significant improvements to facet coatings and passivation. At that time, COMD was the main limiting factor for the output power of the diodes, as the facets were not robust enough to withstand higher intensities. Advances in facet technologies, combined with improvements in epitaxial-level efficiency and consistency, as well as the decline of impurities in wafer processing, have meant that the power-limiting factor may no longer the diode bar itself, but the ability of the cooling technology to dissipate the heat quick enough. As cooling capacities rapidly keep pace with advances in output power, QCW average output power can be expected to increase rapidly as well. Future developments of kW-class diode laser bars should focus on these key factors for performance and cost

We prioritize the following key areas for future developments of kW-class diode laser bars and stacks/arrays made of them:

- **Improving electro-optic efficiency at high brightness:** For kW-class bars, challenges include efficiency reductions due to excess temperature rise, increased ohmic (I^2R) heating at high currents, and reduced differential quantum efficiency due to several phenomena occurring at high current and cavity photon densities.[Wenz] Development activities that may advance pump efficiency include
  - **Chip and epitaxial design** – Novel epitaxial design for reduction of modal absorption, and increased efficiency can provide increased efficiency. Lateral design concepts can increase the brightness of individual emitters by reduction of slow-axis (SA) divergence angle. Far-field angles around 10° (95% P.I.) at the operating point are already realized. Advanced simulation and modelling (for example combined analysis of device and external optical systems [Ada21]) can assist such development.
  - **Enhanced thermal management technology**—methods that reduce thermal impedance and improve heat extraction, without compromising diode lifetime or

    brightness. This includes development of a compact low-cost package with for arrays with very high-power densities in the multi-10 kW/cm² range. Laser cavity bar length, together with device design and cooler material must be fine-tuned to optimize performance.

- **Advancing diode reliability and MTTF assurance:** IFE power generation will require a diode MTTF greater than 10 Gshots. Meeting this demanding requirement without compromising diode brightness is an important requirement for practical IFE deployment. Technologies that improve MTTF and that reduce the time and expense of validating MTTF expectations are important to address this need. These include
  - **Improvements in semiconductor manufacturing technology** – Increase reliability by low defect epitaxial growth and semiconductor processing. Reduction of residual point defect densities will improve gradual degradation rates and delay the onset of facet damage driven by point defect nucleation. Optical damage induced failures can be mitigated by improvements in crystal growth and technology that decreases or eliminates absorption at the laser diode facets. Aim for high yield production to maintain costs.
  - **Advances in facet technology** – Advances in facet passivation technologies mitigate the fundamental limit of InGaAs quantum well (QW) catastrophic mirror damage. Standardization of facet passivation technology moves vendors away from home-grown solutions, facilitates improved equipment availability, and opens perspective to significant cost reductions. Progress the scalability of high-volume low-cost facet passivation and standards for reliability tests.
  - **Improved Packaging technology** – Optimizing packages to minimize thermal loads, and reduction of stress in bar packaging by engineering of solder together with the submount and cooler stack
  - **Methodologies for reliability assurance** – Verifying that a particular diode component will meet the demanding MTTF requirements of IFE is currently a slow and expensive undertaking, due to the long test times required. As laser diode technology pushes to greater power per bar and higher brightness, methods for quickly assessing the viability of new designs (that is, the likelihood of achieving MTTFs in the 10 Gshot range) will provide a key enabler to accelerate the design cycle. This includes R&D to improve understanding of failure precursors and their signatures (in epimaterial, on surface facets, and in package structures and bonding joints) as well as refining methods to accelerate MTTF testing.

- **Pump diode cost reduction –** the economics of power production will require pump diode price points of a few US$0.01/Watt. While significant price reductions are expected from the large production volumes needed for IFE facilities, technologies that drive cost reductions will facilitate the transition to IFE-driven power. Topics that focus on this topic include
  - Advanced manufacturing processes for reduced cost. This may include automation of precision assembly processes, such as bar-to-submount attach and collimator alignment and attach. Technologies for tighter control of bar pitch and smile can enable lower-cost collimator packaging.
  - Cost-reduced fabrication of precision sub-components. Reductions in the cost of precision submounts and fast axis collimators will reduce the cost of packaged diode assemblies.
  - Yield enhancing technologies. Technologies that improve fabrication yields, particularly during packaging, will improve diode manufacturing costs. This includes automated bar handling to minimize introduction of latent defects, tighter control of solder joints and voiding, and technologies that minimize bar smile.

- **Standardization** — IFE-based power generation will require a supply ecosystem that includes multiple sources of standardized pump diode components. Multiple aspects of diode technology should be standardized to facilitate IFE power, including
    - Diode form factor
    - Diode interfaces, including electrical drive and coolant interfaces. Use of a common electrical drive specification will enable a standardized supply of diode drive electronics, which will also be important for implementation at scale.
    - Test methodologies. Performance qualification and assurance at diode-start-of-life should be assessed using a standard set of procedures.
    - MTTF assurance methodologies. Use of a common approach to assessing diode MTTF will be important for assuring that pumps from multiple suppliers can be deployed without compromising power plant availability.

Focusing on diode lasers used as pump sources for high energy lasers, we seek to develop a technical IFE diode development roadmap and set the direction and expectations for future pump diode development. There is an urgent need for strategic development of diode lasers with the goal of providing robust high-power sources at economically feasible price points. Diode technology is an important enabler for IFE. The long timeframes required to develop such technology to market maturity, and to then establish production capabilities consistent with the requirements in supply for an IFE drive demonstrator, will require a continued investment over 5-10 years.

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